HINS Linac Front End
CH Section Focusing Solenoid
Quench Analysis

I. Terechkine

This analysis was needed in order to understand what can happen during testing of the HINS Linac Front End CH section solenoid prototype. A plan for the solenoid test requires separate excitation of the main coil and the bucking coils and then connecting the coils in series. So, we can see a quench in a bucking coil while it is connected in series with the main coil. The collection of materials below analyses the next possible scenarios during the solenoid testing:

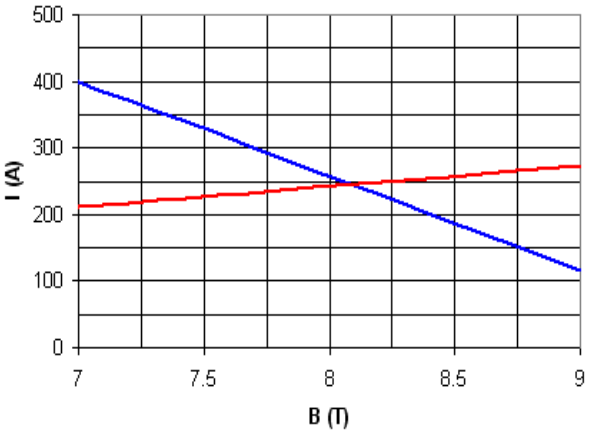
1. Quench in the Stand Alone Main Coil: **MC-SA;**
2. Quench in one of the Bucking Coils when the two of them are connected in series without the Main Coil: **BC-SA** ;
3. Quench in one of the Bucking Coils when the two of them and the Main Coil are connected in series: **BC-MC.**

Quench in the Main Coil connected in series with the Bucking Coils will not be analyzed here because it is almost identical to the case MC-SA. In each case, several quench initiation scenarios are compared that differ by different level of current in the solenoid during quenching and initial location of the quench.

An instrument for the study was specially developed MATLAB-based software described in [1]. A description of the solenoid prototype can be found in [2].

I. MC-SA

The expected quench current is defined by a diagram below:



One expects the maximal current of 250 A with the maximal field in the coil (the center of the first layer) of 8.07 T.

A. Quench occurs in the point of the maximum field

Figures below show time profiles of the coil current, maximal temperature, the coil resistance, and its temperature distribution in the end of a quench event. Also shown is a layer voltage-to-ground time profile. The initial quench location is in the middle of the inner layer. Two columns correspond to two different settings of the initial current:

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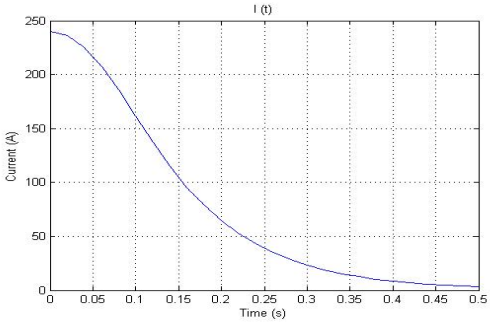
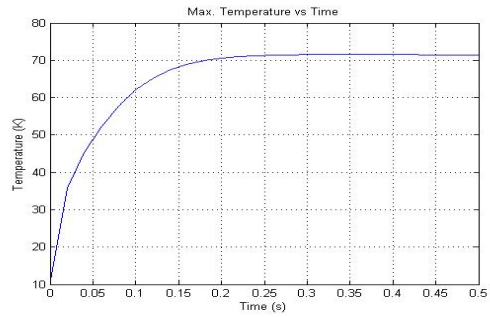
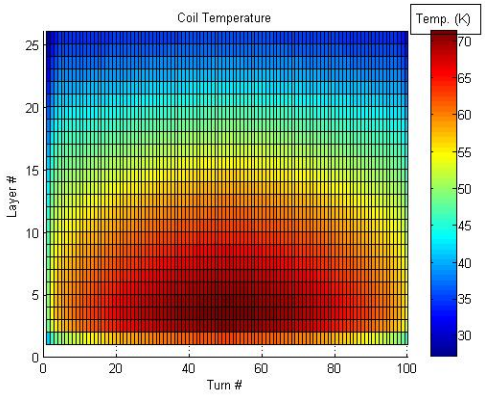
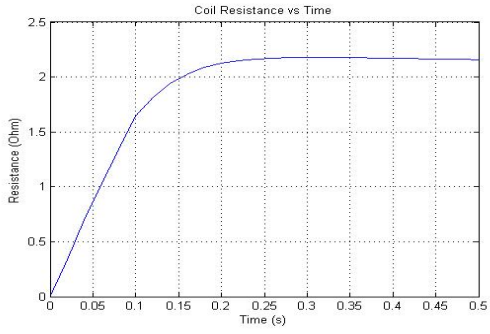
I = 240 A

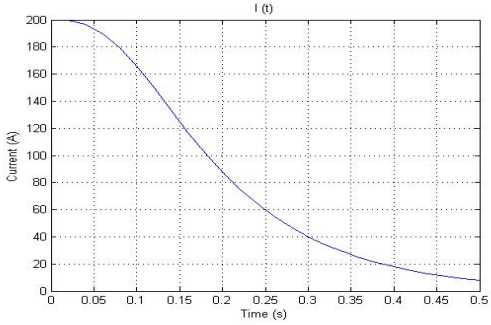


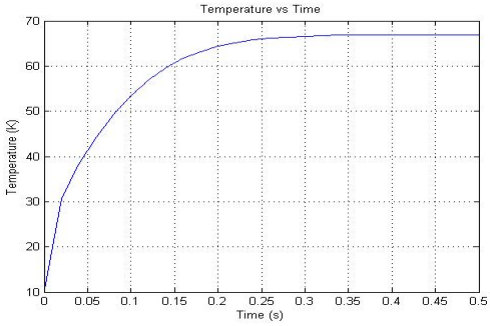


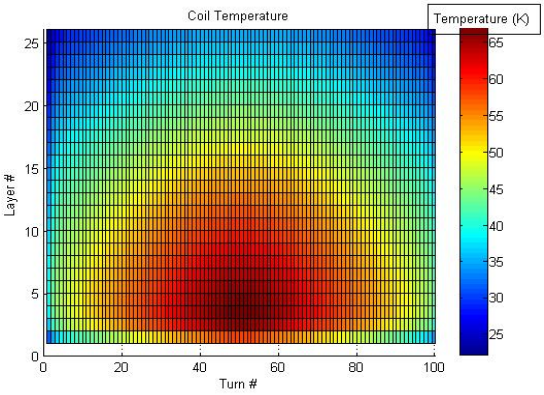


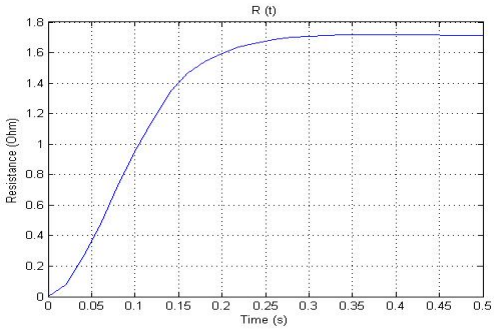


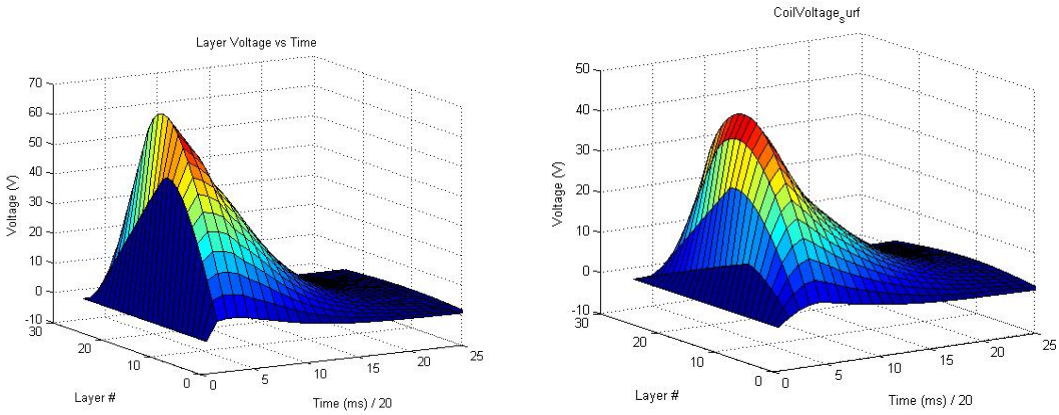
I = 200 A











Maximum voltage-to-ground in both cases develops in the middle of the coil and reaches ~ 70 V if the initial current is 240 A (~ 50 V if it is 200 A). This voltage is positive, which indicates the increase of the resistance of the internal layers due to heating and compensation of this voltage due to inductive component which develops when the current starts decaying. The voltage of the last layer is zero by definition is no dump resistance is used. Adding the dump resistance will significantly increase layer voltage-to-ground.

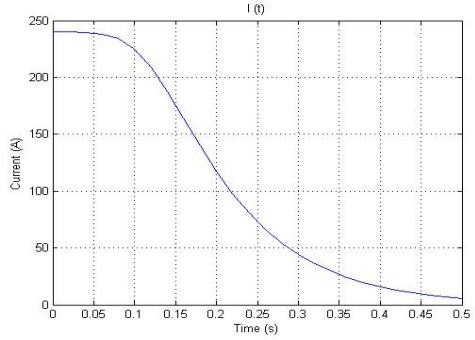
It is possible to notice that although stored energy is almost 1.5 times lower in the case of the 200 A initial current, the maximum temperature is just ~6% lower. This happens because of the reduced quench propagation velocity due to lower magnetic field. Lower energy dissipates in smaller volume of the coil.

Similar situation can happen if the quench location is in the area where the magnetic field is low, so we need to test the main coils and the bucking coils taking this effect into the account.

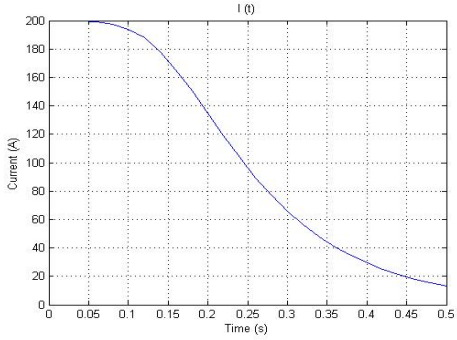
B. The quench occurs in the point of the minimum field

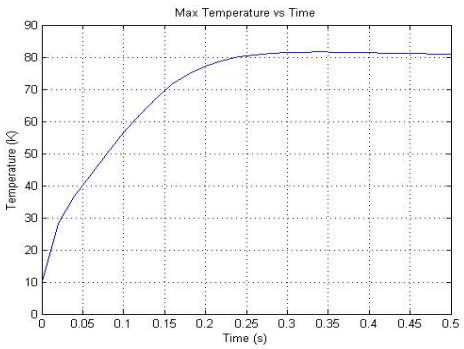
As before, the figures below show time profiles of the current, maximal temperature and coil resistance, as well as the temperature distribution in the end of the quench event and a layer voltage-to-ground time profile. The initial quench location is in the middle of the upper layer, where the magnetic field is close to zero.

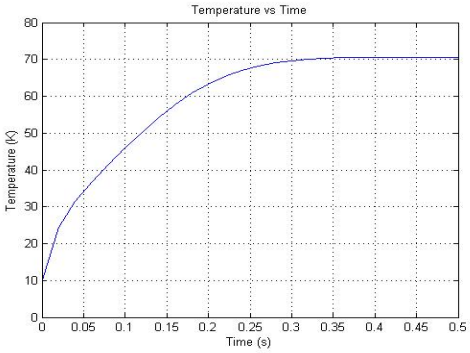
I = 240 A

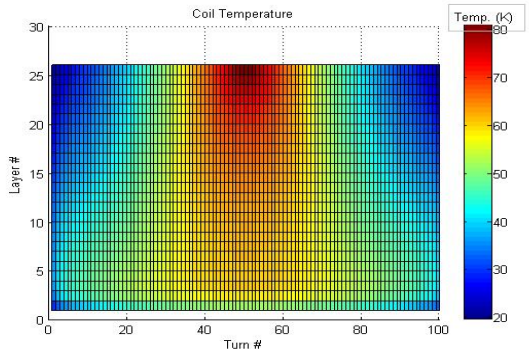


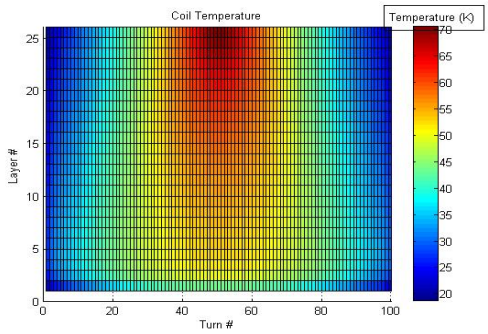
I = 200 A

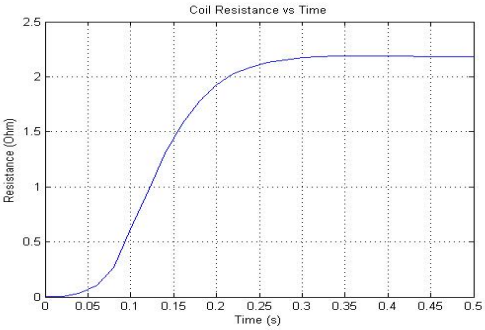


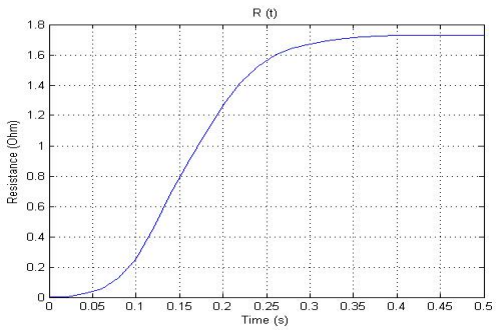


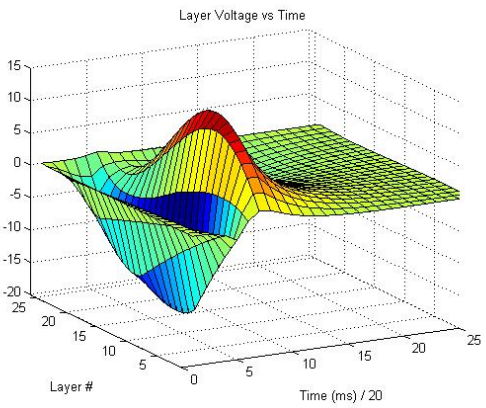


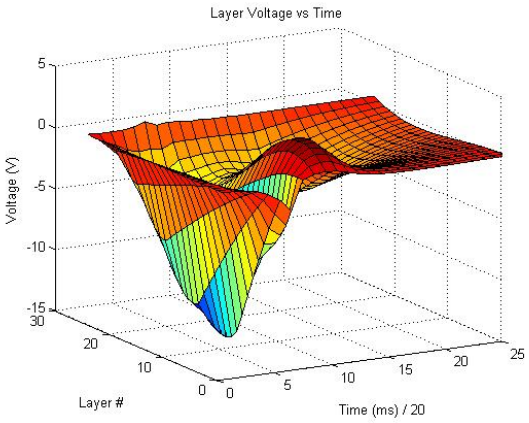












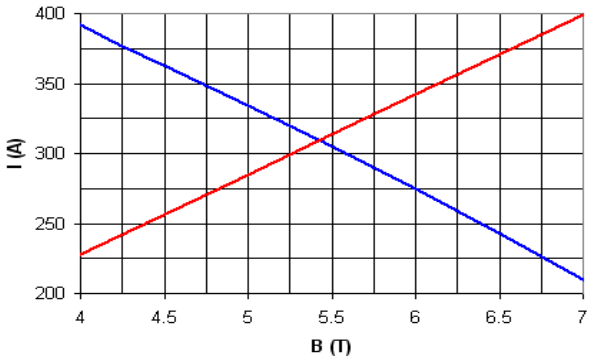
Analyzing the figures above, we can say that although some details of the current and the coil resistance time profiles differ from what we saw in the case of the initial quench

location at the area of the maximum field, global behavior of the coil did not change: maximal temperature is still 70 – 80 K and maximum coil resistance is ~ 2 Ohm. Layer voltage profile differs from what we saw before. The change of the voltage polarity from negative to positive is because the quench starts in the outer layer, so the inner layers first see inductive voltage that is then compensated (and over-compensated) by the resistive voltage of the turns that turned normal. Nevertheless, this voltage is well below the level that would ignite our concern (if there is no a dump resistance in the circuit).

So, the conclusion for the Part I (MC-SA) of this study is that the coil is quite safe to operate at any level of current without elaborate protection. Nevertheless, one must pay attention to recognize a quench event and make a power supply off.

II. BC-SA

If the two bucking coils are connected in series, the expected quench current is defined by a diagram below:

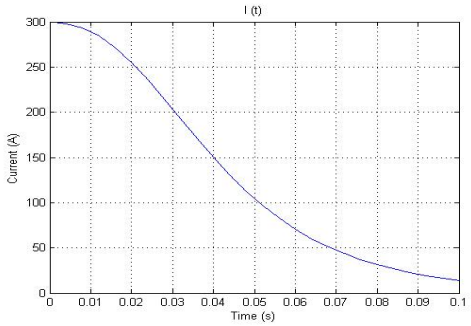


One expects the maximal current of 310 A with the maximal field in the coil (the central part of the inner layer) of 5.4 T.

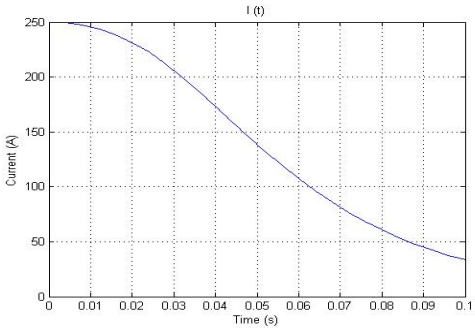
A. The quench occurs in the location of the maximum field

As before, figures below show time profiles of the current, maximal temperature and coil resistance, as well as the temperature distribution in the end of the quench event and a layer voltage-to-ground time profile. The initial quench location is in the middle of the inner layer. Two columns correspond to two different settings of the initial current:

I = 300 A



I = 250 A



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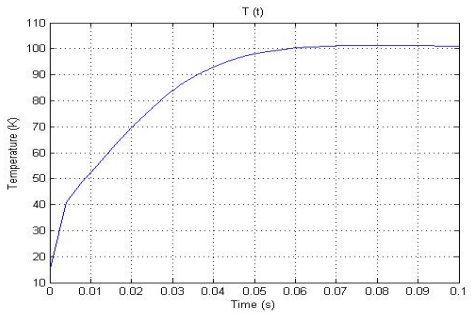
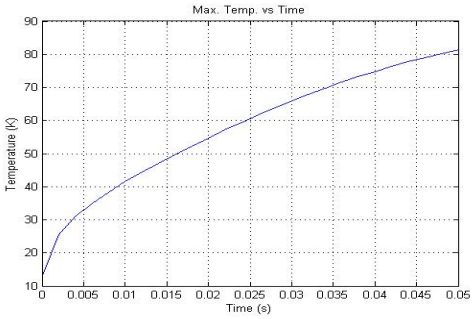
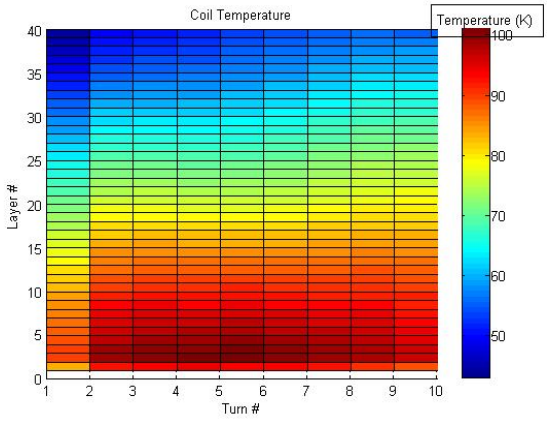
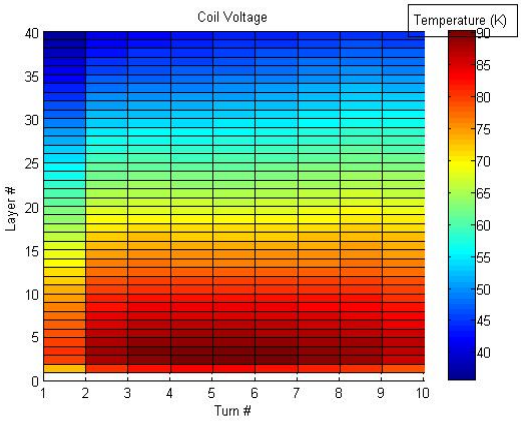
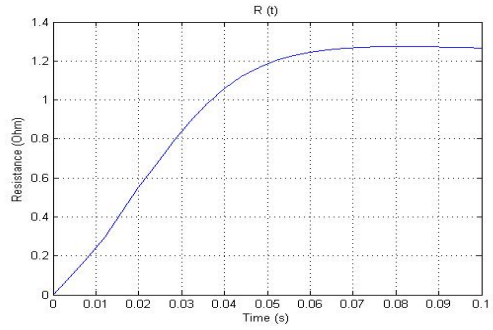
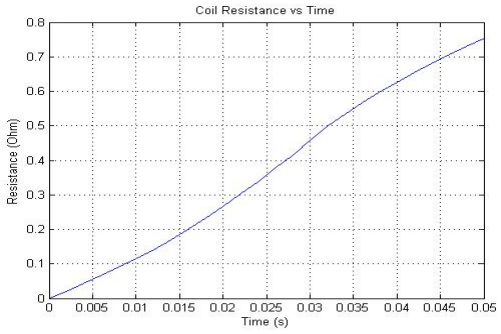


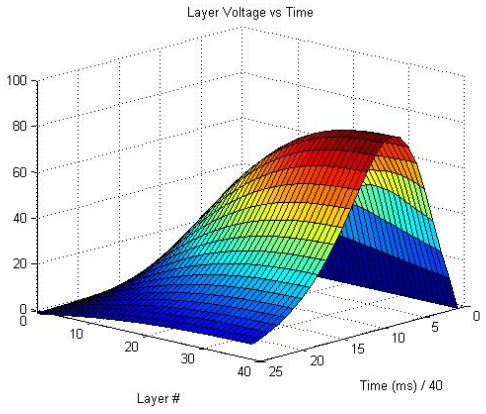


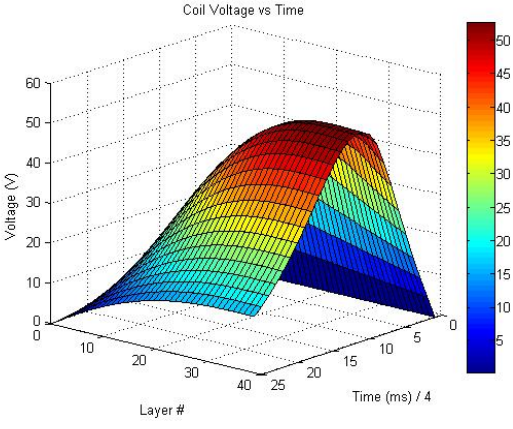










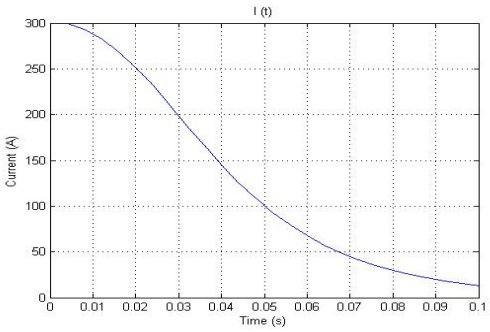


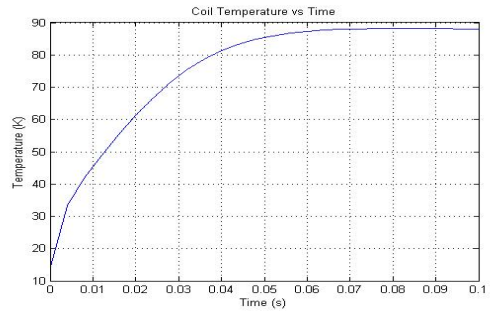
In this case, temperature in the coil does not exceed 100 K, and the maximum voltage is on the level of 100V at 300 A. In the case of the bucking coils, the maximal voltage is in the last layer because of the additional inductance that comes with the second coil. If we would try the second coil for quench, this voltage would turn negative.

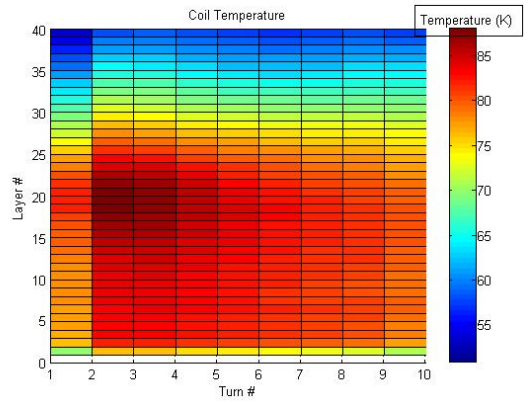
B. The quench occurs in the location of the minimum field

The initial quench location is in the middle of the outer side of the coil (layer 20). Two columns correspond to two different settings of the initial current:

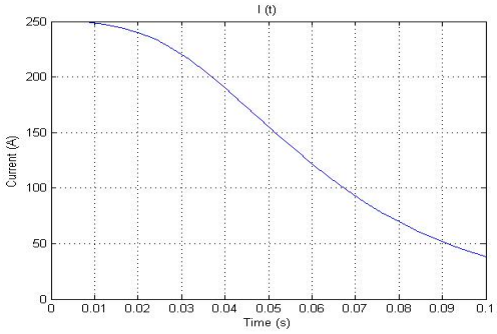
I = 300 A

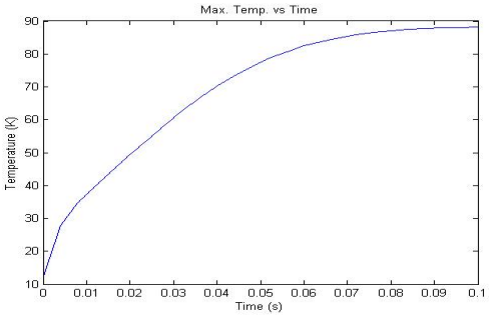


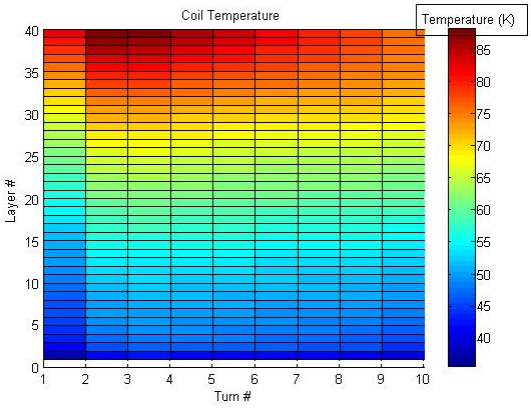


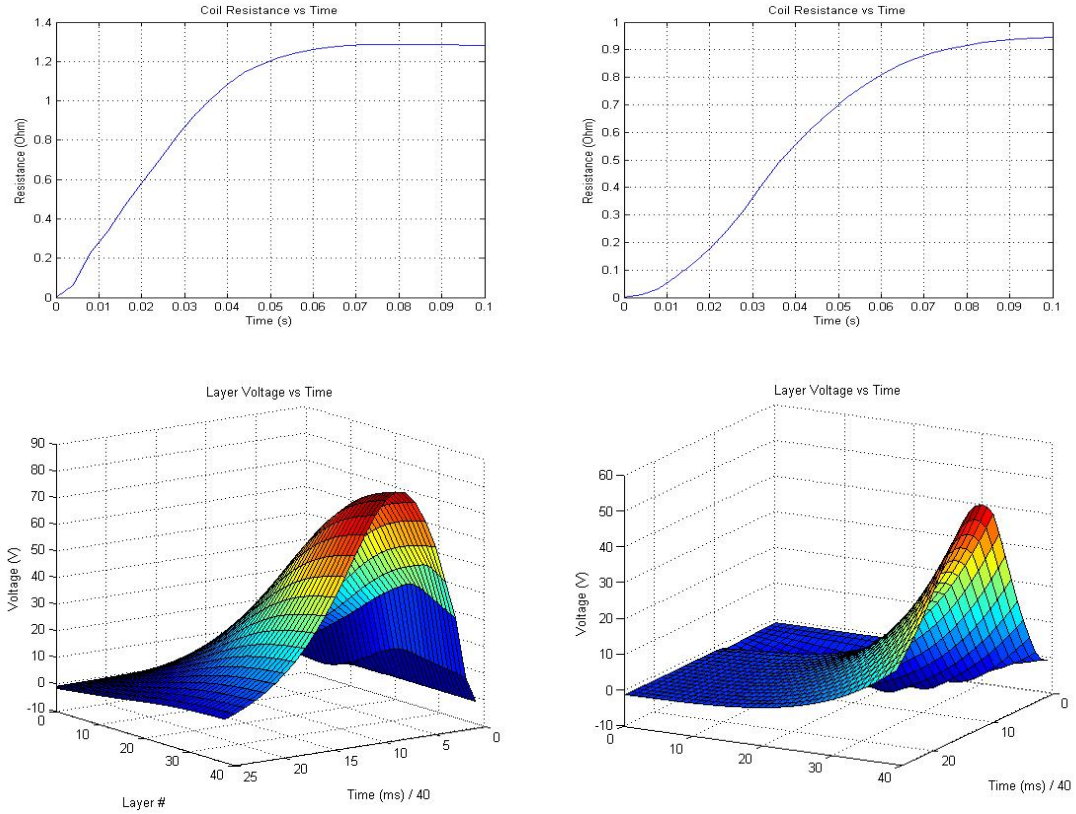


I = 250 A









Again, although some features of the quench process changed, the total conclusion is that it is relatively safe to operate the bucking coils at any current level. Quench starting from different locations does not result in an excessive temperature growth or high voltage on the layers of the coil. The maximal voltage of ~ 100 V can be expected on the outer layer of the coil.

III. BC-MC

In this case, the maximal current can not exceed that of the main coil, which is ~ 250 A. Because the main coil connected in series with the bucking coils, relatively high energy can dissipate in a relatively small volume of bucking coil resulting in an elevated coil temperature.

A. The quench occurs in the location of the maximum field

As before, figures below show time profiles of the current, maximal temperature and coil resistance, as well as the temperature distribution in the end of the quench event and a layer voltage-to-ground time profile. The initial quench location is in the middle of the inner layer. Two columns correspond to two different settings of the initial current:

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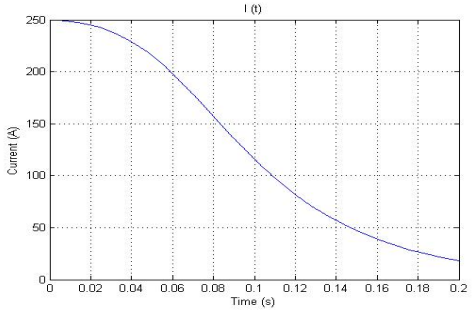
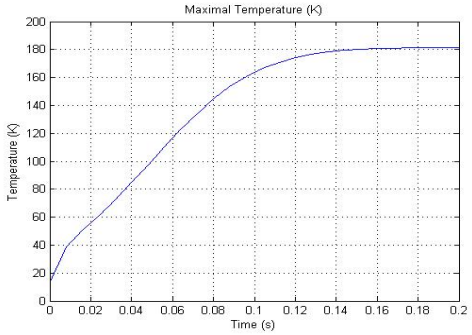
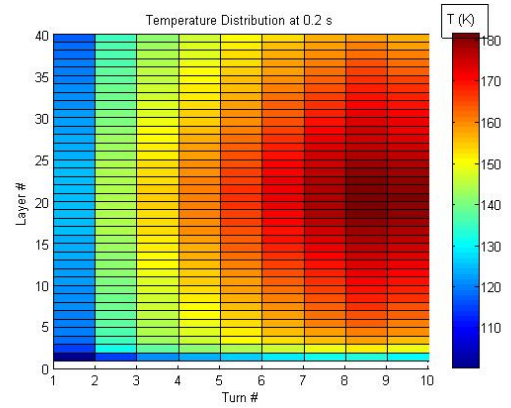
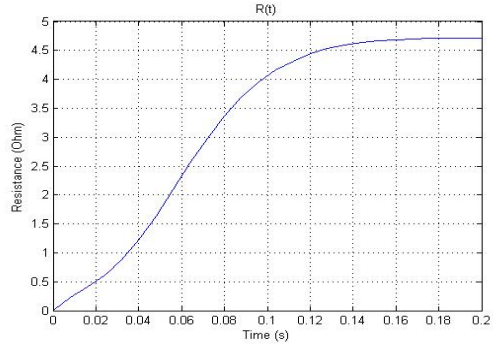
I = 250 A

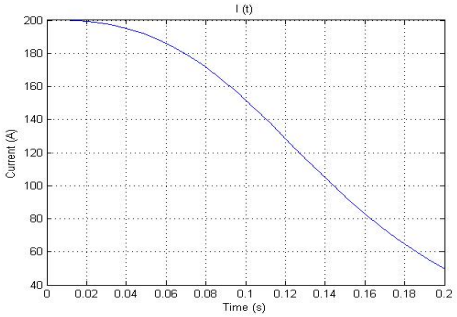


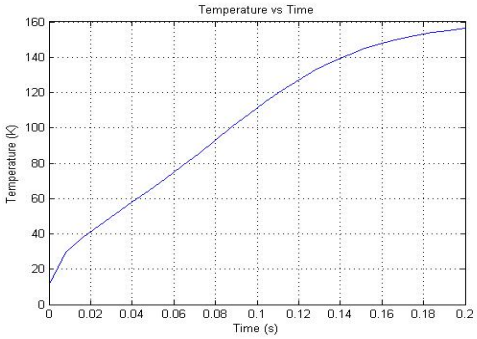


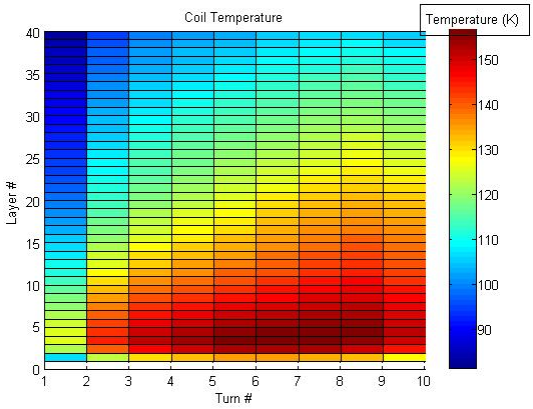


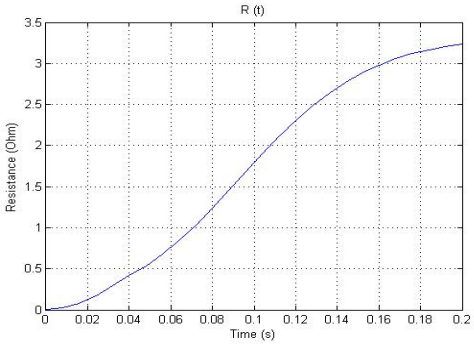


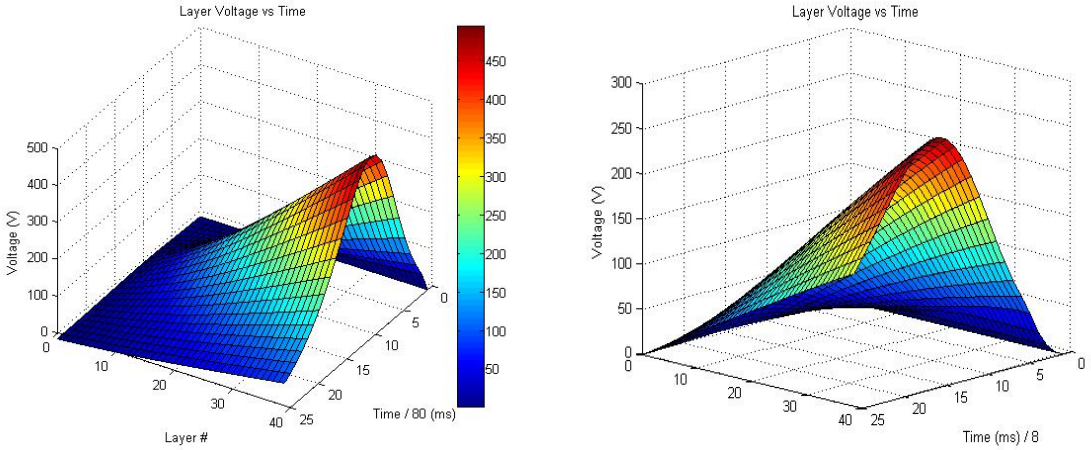
I = 200 A



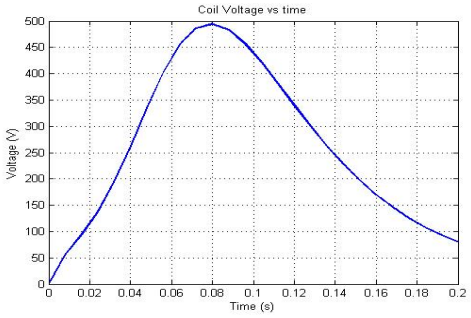








In this case, the Bucking Coil temperature reaches 180 K, which still seems acceptable. Voltage is maximal at the outer layer (#40) and reaches ~ 500 V at ~ 80 ms (see the layer voltage chart below).

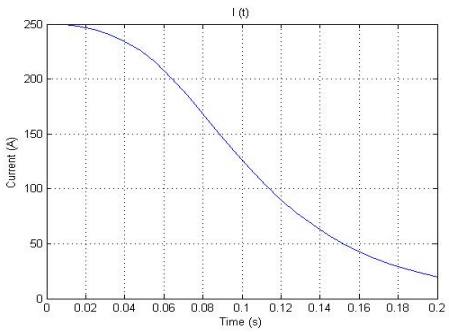


At this moment, the coil resistance is ~ 3.5 Ohm, which is much higher than the available 0.6 Ohm dump resistance. This fact points to paying some attention to choosing an optimal value for the dump resistance in order to limit the voltage growth. This analysis deserves a separate study.

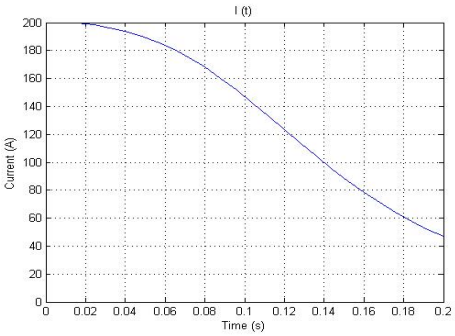
B. The quench occurs in the location of the "minimal" field

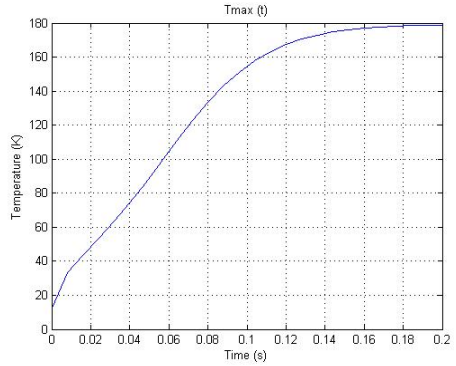
In this configuration, the minimal magnetic field is on the outer side of each bucking coil, approximately in the middle of the side (layer # 20, turn # 1).

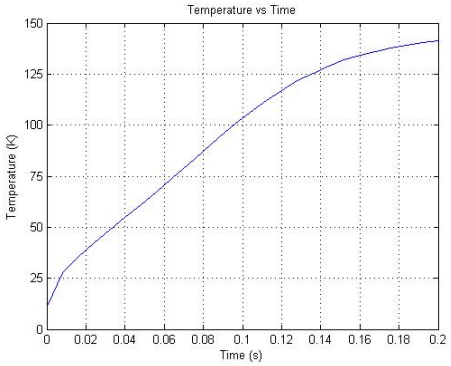
I = 250 A

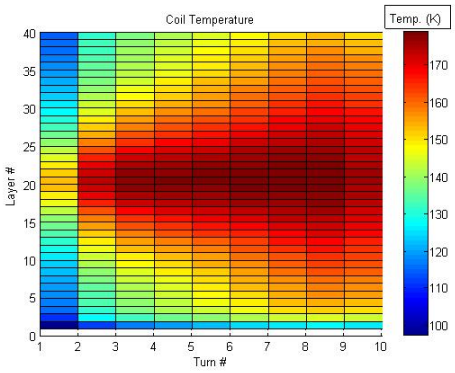


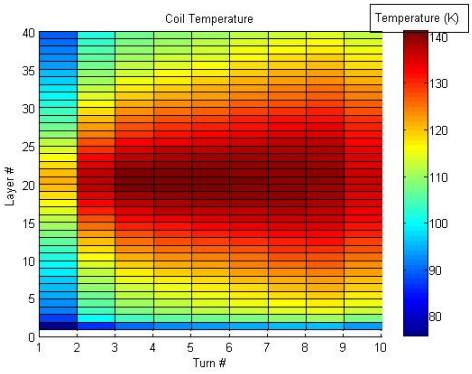
I = 200 A

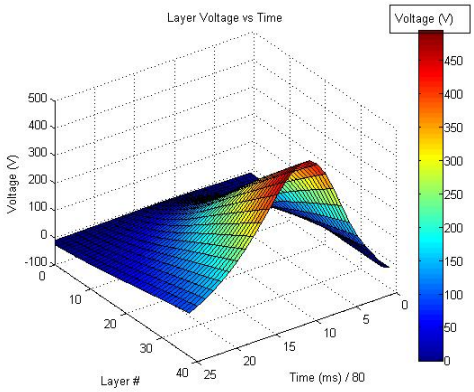


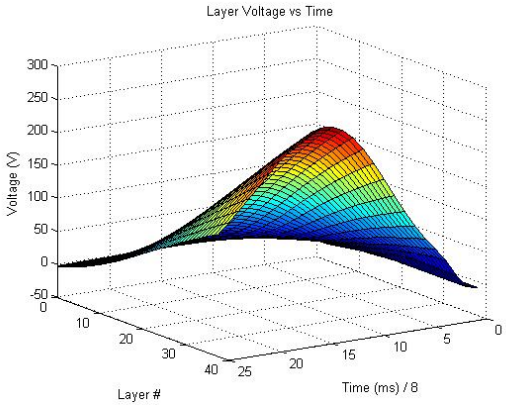












Although details of the temperature distribution are different in cases of the maximum field and the minimum field quench initiation, there is small difference in the maximum temperature and the coil voltage for I = 250 A.

IV. Conclusion

The results of this study show that the most dangerous situation from the point of view of quench protection can happen when the bucking coils are used with the main coil at maximal current of ~ 250 A. In this case the temperature of the coil can reach ~ 200 K and the maximal voltage is ~ 500 V without any dump resistance in the circuit. A dump resistor can reduce the maximal temperature, but also can increase the maximal voltage. A special study must be devoted to this issue to ensure safe work of the system.

References:

1. S. Obraztsov, I. Terechkine, “A Tool for Modeling Quench Propagation and Related Protection Issues”, FNAL TD-06-063, December 2006.
2. G. Davis, V.V, Kashikhin, T. Page, I. Terechkine, T. Wokas, “Linac CH-Type Section Focusing Solenoid Cold Mass Design”, FNAL TD-06-020, March 2006.